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Nikhef

cLFV @ LHCb

Status & Prospects

Gerco Onderwater
on behalf of the LHCb collaboration

cLFV2016, Charlottesville VA, USA, 20-22 June 2016

Outline

Intro

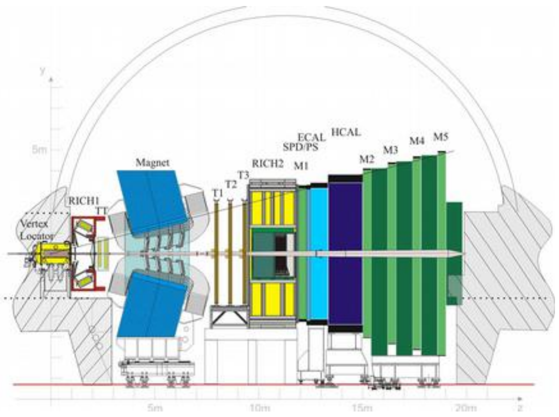
LHCb Experiment

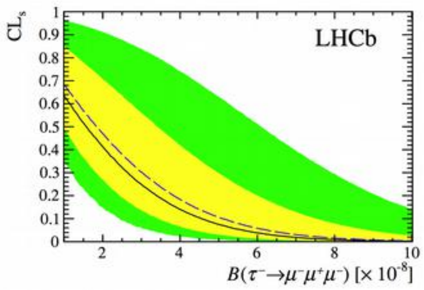
LFV with muons : τ→μμμ

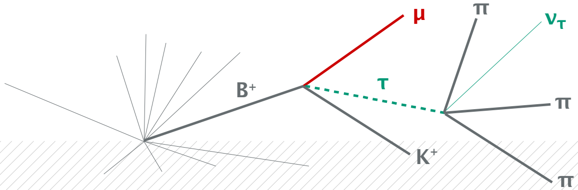
LFV with electrons : D^0→eμ

LFV with taus?

Conclusion







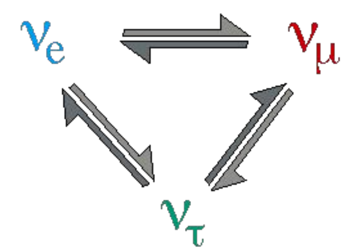
Intro

Standard Model

Remarkably successful,
yet with many unexplained features

Many puzzles, *e.g.* 3 generations quarks & leptons

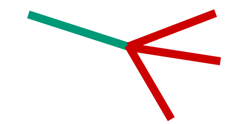
Rich symmetry-driven phenomenology



Study <u>all</u> generations for full insight

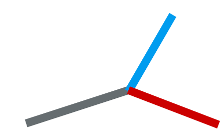
LHCb: can study all three generations

Towards studying (c)LFV



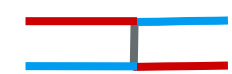
Decay $\mu\to e\gamma$, $\mu\to eee$, $\tau\to\mu\mu\mu$, $\tau\to\mu hh$, ...

Conversion $\mu A\to eA$



Production $B_s\to e\mu$, $B\to Ke\mu$, $h^0\to\mu\tau$, ...

Oscillation $\nu_e\leftrightarrow\nu_\mu\leftrightarrow\nu_\tau$, $M(\mu^+e^-)\leftrightarrow\overline{M}(\mu^-e^+)$



Number violation $0\nu2\beta$, $B^-\to\pi^+\mu^-\mu^-$, ...

Non-Universality $\overline{B}^0\to D^{*+}\tau^-\overline{\nu}_\tau$ *vs* $\overline{B}^0\to D^{*+}\mu^-\overline{\nu}_\mu$, ...

Charges dropped, unless relevant

Tensions

$B^0 \rightarrow D(^*)\, \tau\bar{\nu}_\tau \,/\, l\bar{\nu}_l$ **3.9σ** : LHCb + BaBar + Belle

$B^+ \rightarrow K^+\mu\mu \,/\, ee$ **2.6σ** : LHCb

Anomalies **b → sll** , esp. P'_5 in **B → K*μμ** @ LHCb

$h^0 \rightarrow \mu\tau$ **2.4σ** : CMS

a_μ **2.7σ** : E821

Global fit favors large cLFV

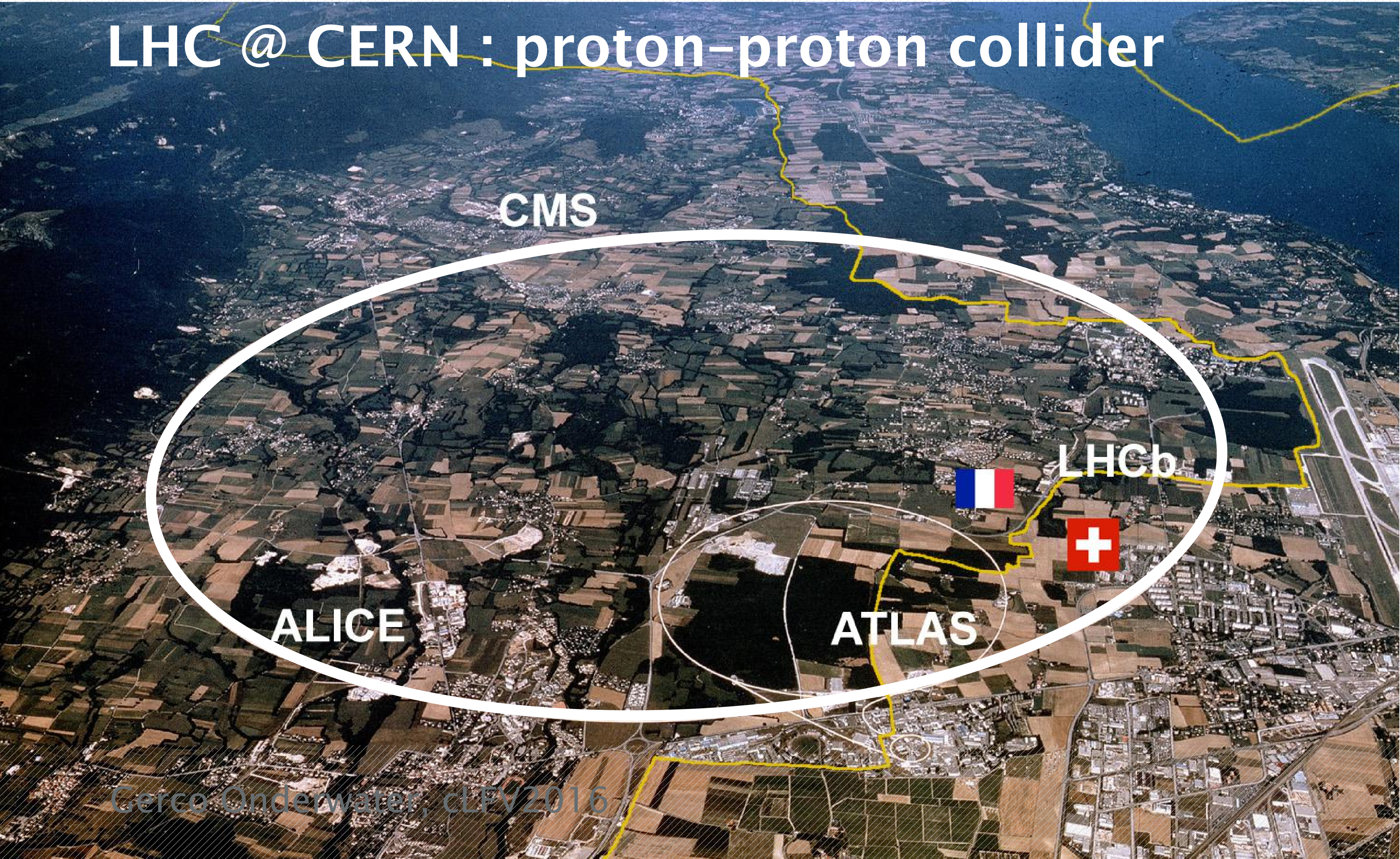
FERMILAB-PUB-16-131-T

Recent LHCb results

$D^0 \to e\mu$	PLB 754 (2016) 167	**LFV**
$\overline{B}^0 \to D^{*+} \tau\overline{\nu}_\tau$ / $\mu\overline{\nu}_\mu$	PRL 115, 111803 (2015)	LNU
$\tau \to \mu\mu\mu$	JHEP 02 (2015) 121	**LFV**
$B^+ \to K^+\mu\mu$ / ee	PRL 113, 151601 (2014)	LNU
$B^- \to \pi^+\mu^-\mu^-$	PRL 112, 131802 (2014)	*LNV*
$D^+_{(s)} \to \pi^-\mu^+\mu^+$	PLB 724 (2013) 203-212	*LNV*
$B^0_{(s)} \to e\mu$	PRL 111 (2013) 141801	**LFV**

LHCb

LHC @ CERN : proton-proton collider



LHCb detector

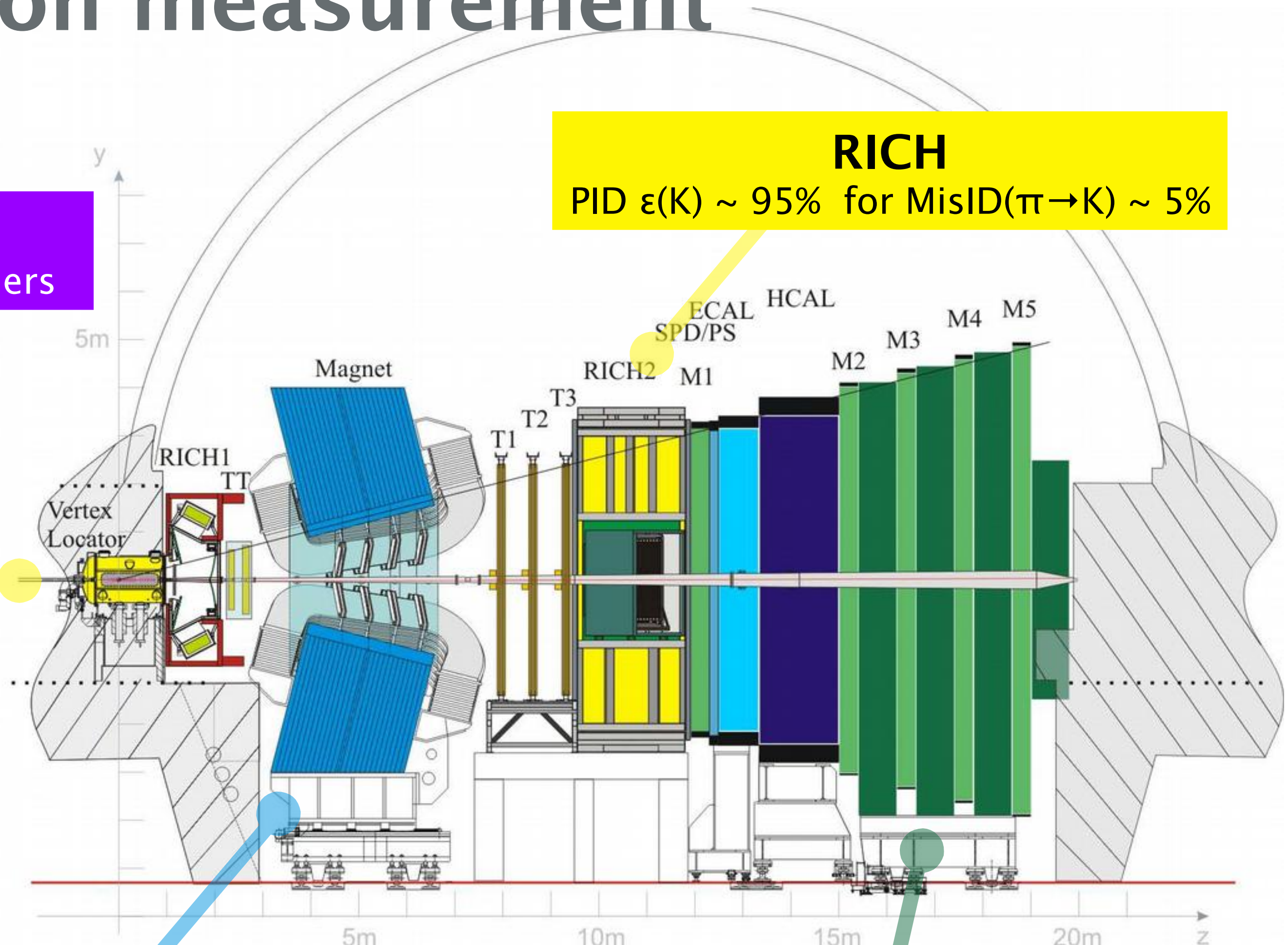
LHCb detector

LHCb : precision measurement

Trigger
high efficiency *esp.* muon triggers

RICH
PID ε(K) ~ 95% for MisID(π→K) ~ 5%

VELO
~20μm IP resolution for $p_T > 2$ GeV



Tracking Δp/p
0.4% @ 5 GeV/*c* – 0.6% @ 100 GeV/*c*

Muon ID
identification ε ~ 97% misID ~ 2%

Int. J. Mod. Phys. A 30, 1530022 (2015)

b-quark production

Acceptance

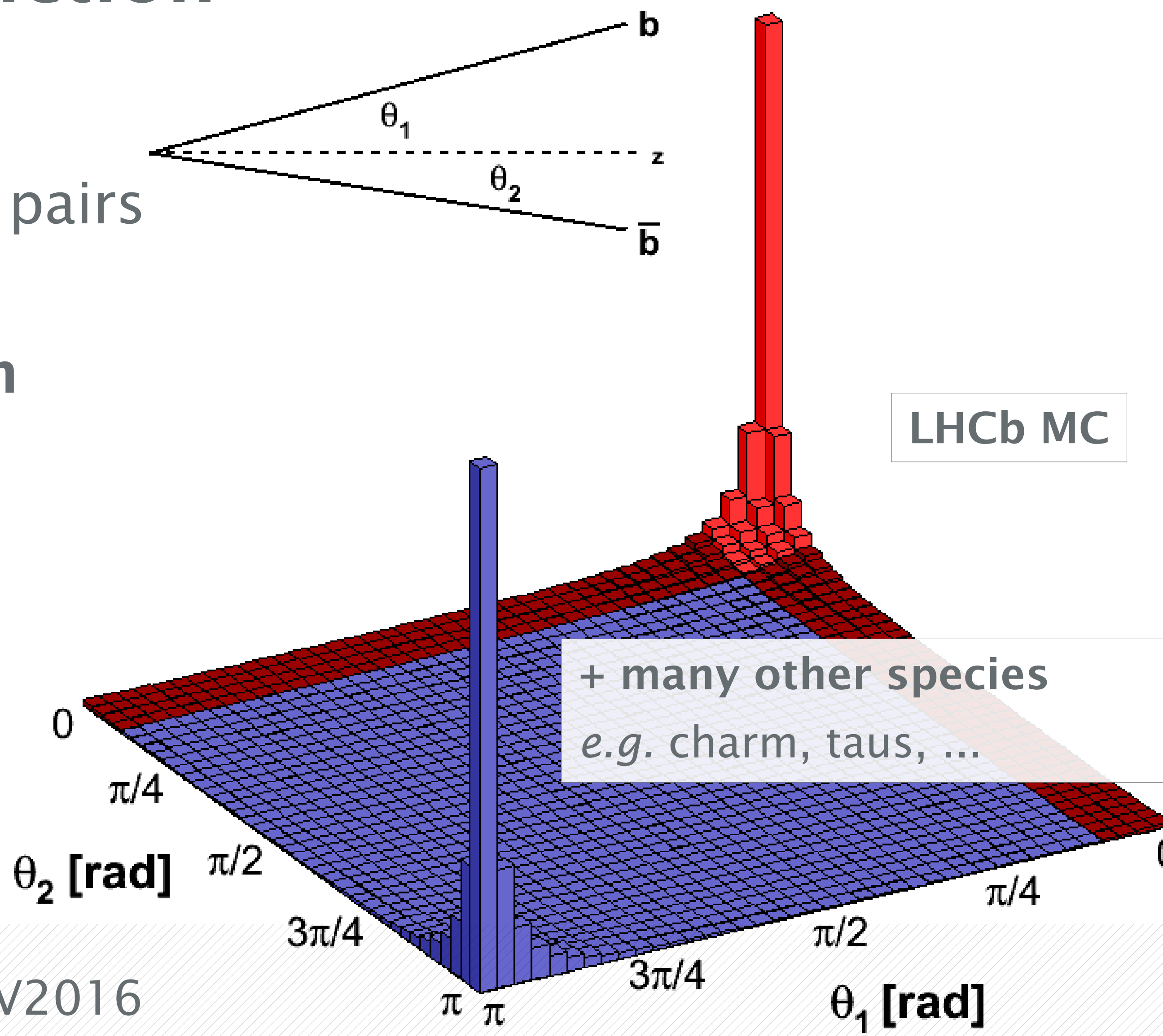
~25% for $b/\bar{b}$ or $b\bar{b}$ pairs

Total cross section

250μb – 500μb

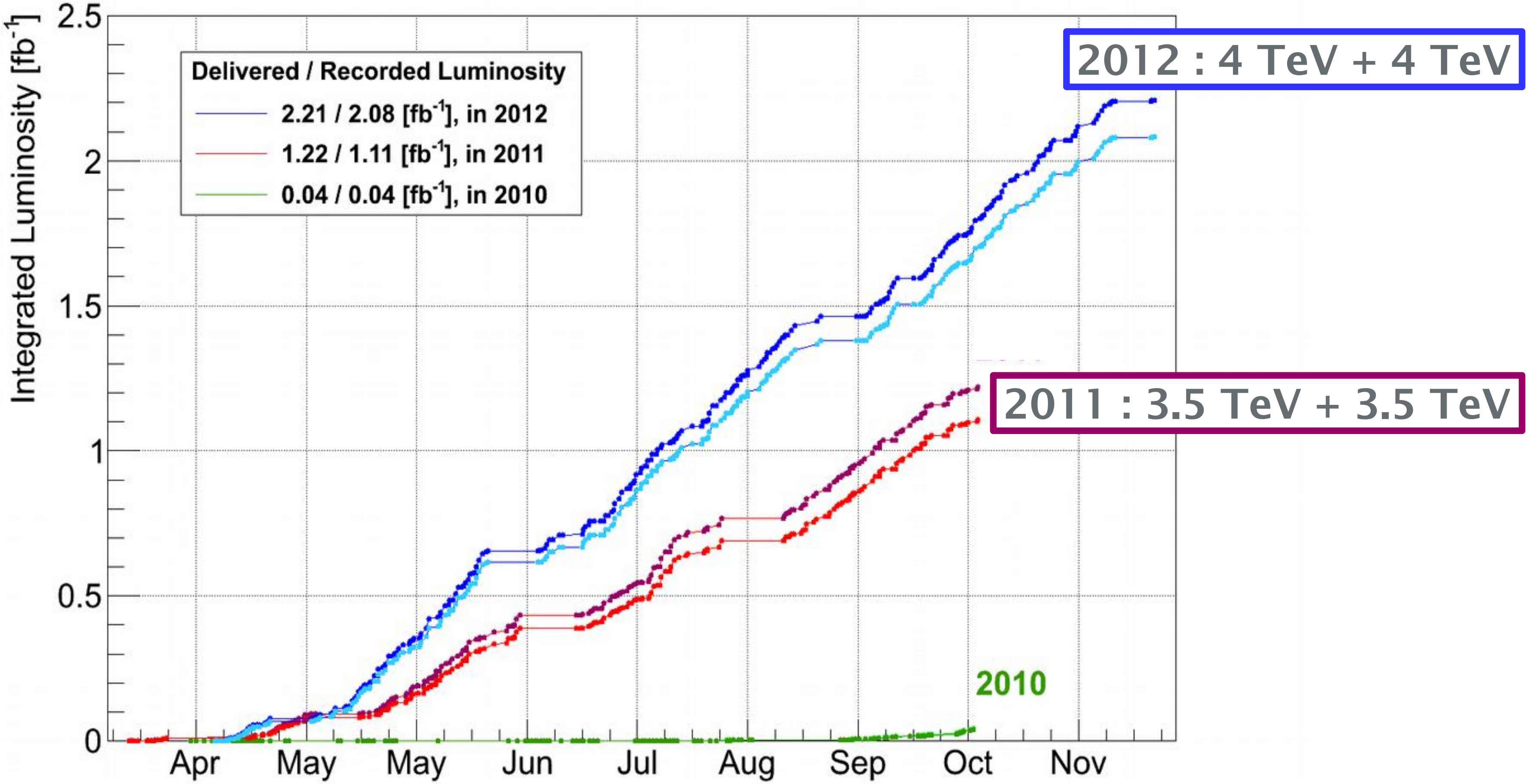
10^5 $b\bar{b}$ / s

(10^4 x B-factories)

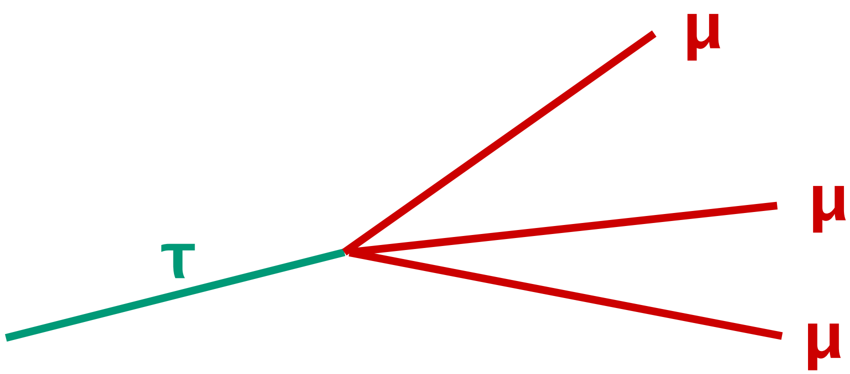


+ many other species
e.g. charm, taus, ...

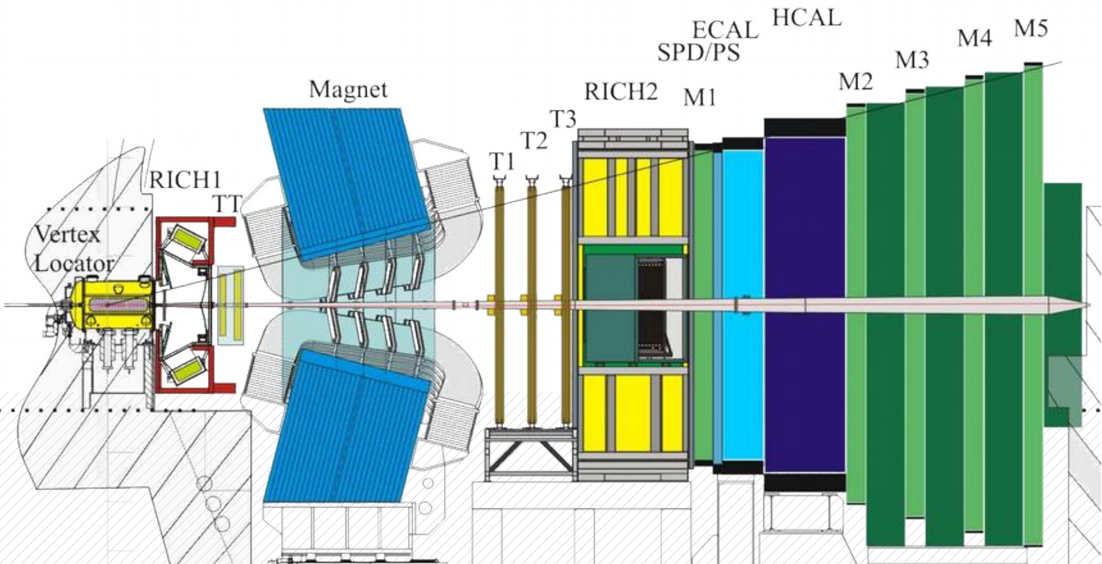
LHC run-I luminosity



Results


μ
μ
μ
τ

μ detection


Vertex Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5

Challenge : τ decays at hadron collider

B factory

- ✘ Babar & Belle ~3x10⁹ τ-pairs
- ✓ $e^+e^- \rightarrow \tau^+\tau^-$ extremely clean
- ✓ tag with opposite τ possible

LHC

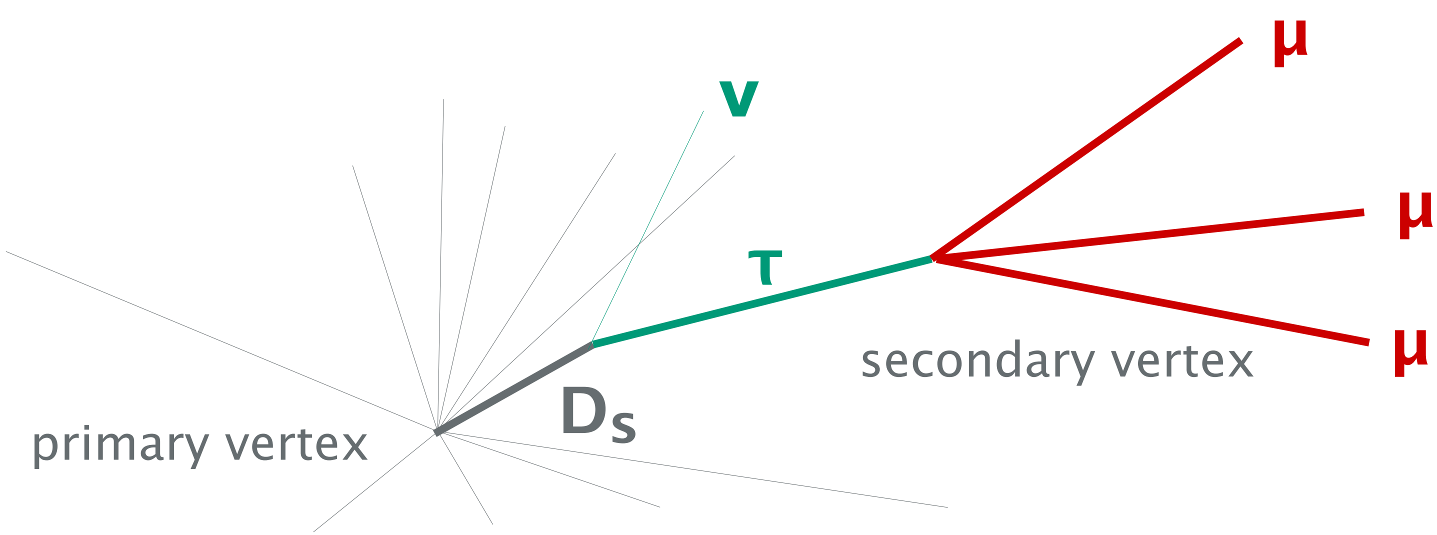
- ✓ LHCb ~3.5×10^{11} τ's in detector acceptance in 2011 & 2012
- ✘ $pp \rightarrow \tau + O(100)$ particles
- ✘ No "production traces" in $D_s \rightarrow \tau\nu_\tau$
- ✘ Charm decay with missing particles similar to τ signature

$\tau \to 3\mu$ search

Approach:

- Use run-I data
- trigger on *muon* and *secondary vertex*
- *multivariate analysis* to discriminate signal and background
- *control sample* for normalization and calibration

main tau production via decay of D_s



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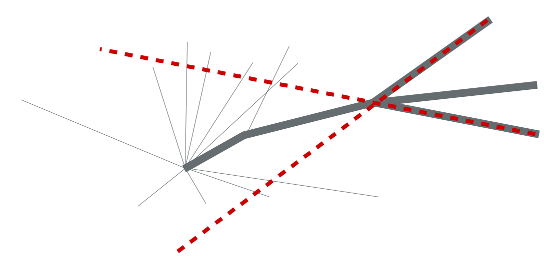
Signal candidate selection

Trigger

- muons not "in beampipe" ($p_T > 1.48$ GeV/c)
- two-, three- or four-track secondary vertex
- at least one particle does not point to collision point

Analysis

- no tracks may point to collision point
- good 3-track vertex
- decay-time compatible with τ decay ($c\tau > 100$ μm)
- τ momentum must point back to PV



Background elimination

- $|M(\mu^+\mu^-) - M(\phi)| > 20$ MeV/c^2 — $D_s^- \to \phi(\mu^+\mu^-)\pi^-$
- $M(\mu^+\mu^-) > 450$ MeV/c^2 — $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$
- $M(\mu^-\mu^-) > 250$ MeV/c^2 — reconstructed from same particle

JHEP 02 (2015) 121

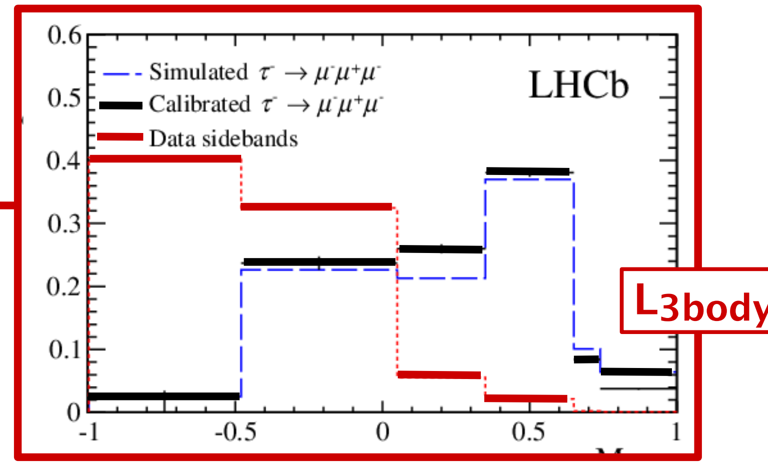
Signal & background discrimination

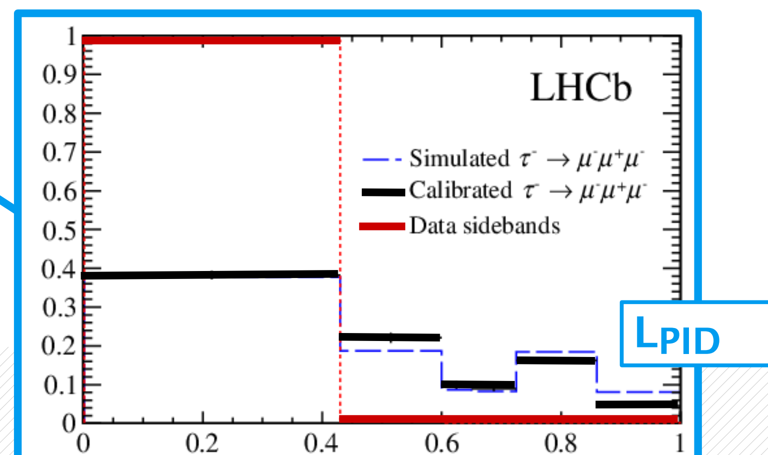
Three likelihoods to distinguish signal from background

I. L_{3body} : decay topology

II. L_{PID} : μ identification

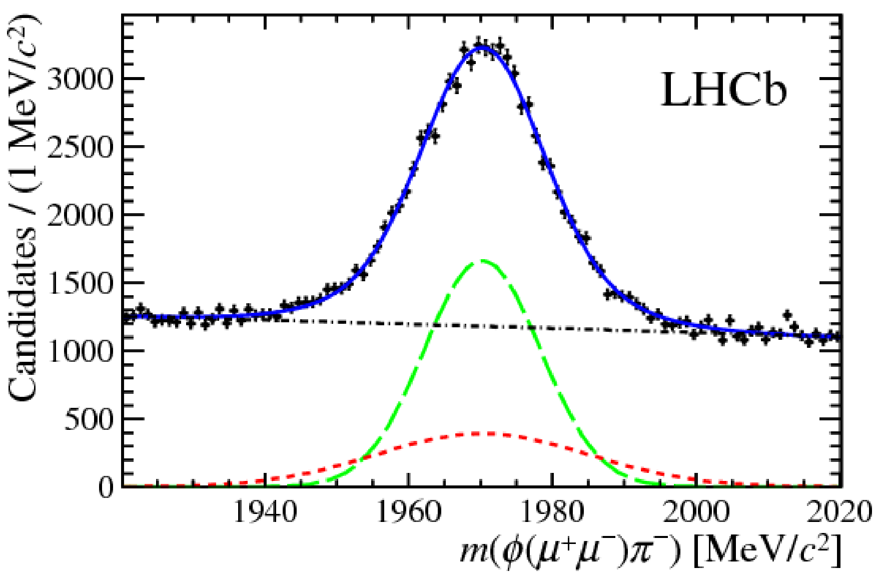
III. $L_{3\mu}$: tau selection



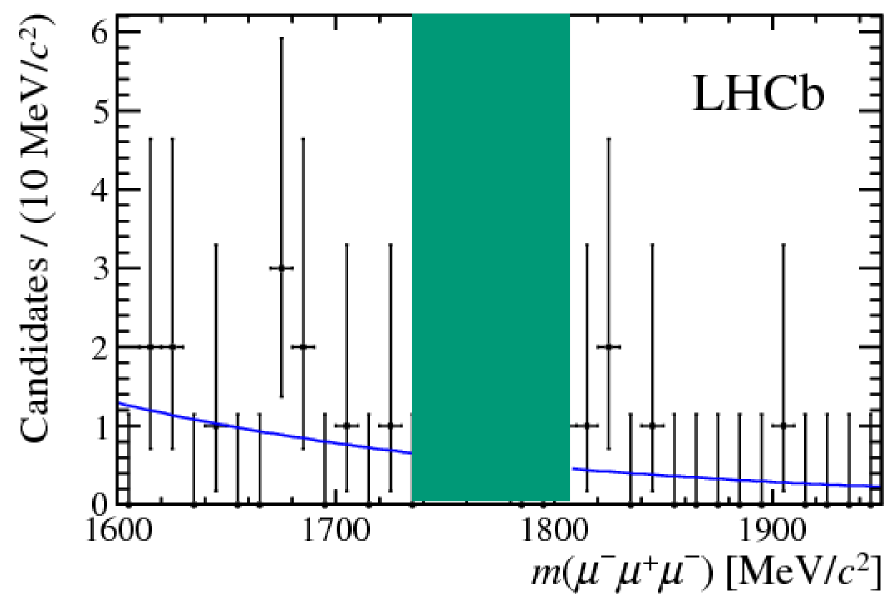


$M_{3\mu}$ distribution

- Shape determined using $D_s^- \to \phi(\mu^+\mu^-)\pi^-$
- Analyze 5x5 best bins in L_{PID} and L_{3body}



Blind analysis



L_{PID} : [0.65, 1.0]
L_{3body} : [0.725, 1.0]

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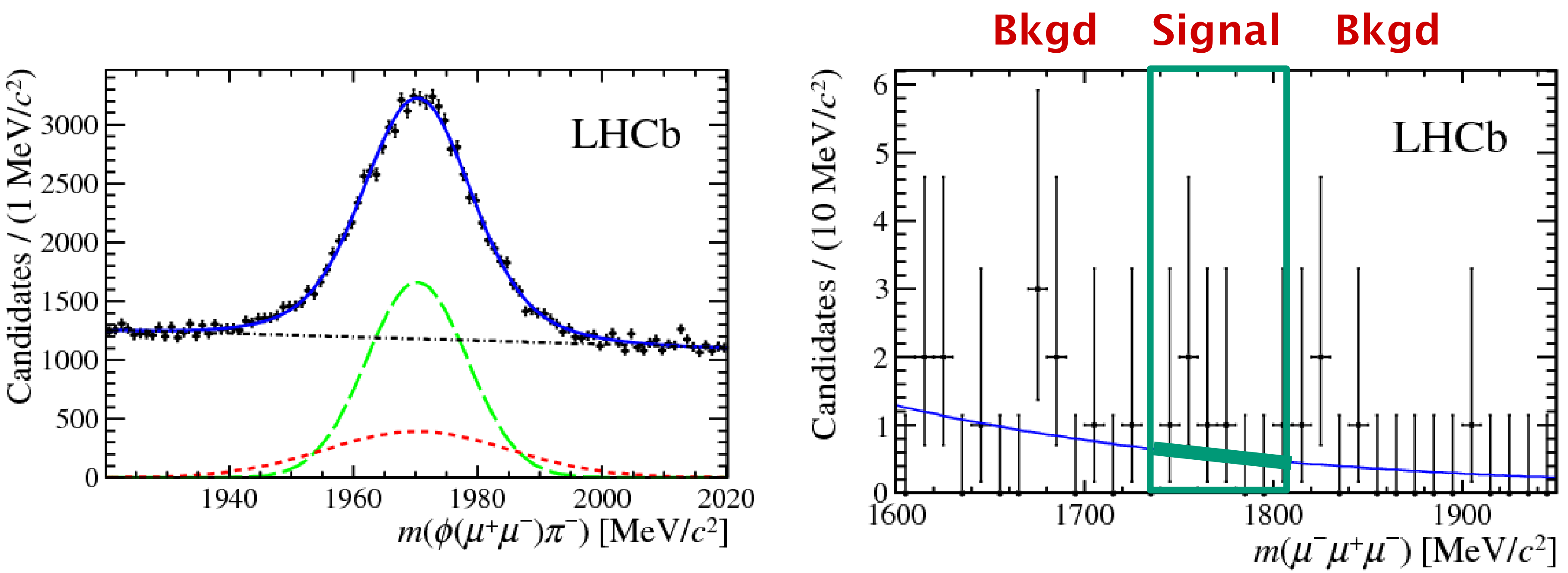
$M_{3\mu}$ distribution

- Shape determined using $D_s^- \to \Phi(\mu^+\mu^-)\pi^-$
- Analyze 5x5 best bins in L_{PID} and L_{3body}



L_{PID} : [0.65, 1.0]
L_{3body} : [0.725, 1.0]

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Normalization

Branching fraction for $\tau^- \to \mu^-\mu^+\mu^-$ normalized to $D_s^- \to \Phi(\mu^+\mu^-)\pi^-$

$$B = \frac{N(\tau \to \mu\mu\mu)}{N(\tau)} = \alpha \times \frac{N_{sig}}{N_{cal}}$$

$$\alpha = \frac{N_{cal}}{N(\tau)}$$

	7 TeV	8 TeV
$\mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-)$	$(1.32 \pm 0.10) \times 10^{-5}$	
$\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)$	$(5.61 \pm 0.24) \times 10^{-2}$	
$f_\tau^{D_s}$	0.78 ± 0.04	0.80 ± 0.03
${\epsilon_{\rm cal}}^{\rm R}/{\epsilon_{\rm sig}}^{\rm R}$	0.898 ± 0.060	0.912 ± 0.054
${\epsilon_{\rm cal}}^{\rm T}/{\epsilon_{\rm sig}}^{\rm T}$	0.659 ± 0.006	0.525 ± 0.040
$N_{\rm cal}$	$28\,200 \pm 440$	$52\,130 \pm 700$
α	$(7.20 \pm 0.98) \times 10^{-9}$	$(3.37 \pm 0.50) \times 10^{-9}$

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Result

$$\frac{\mathbb{P}(\theta_{up}(X) < \theta|\theta)}{\mathbb{P}(\theta_{up}(X) < \theta|0)} \leq \alpha' \text{ for all } \theta.$$

- Robust analysis method
- Statistics limited
- No significant evidence for excess of events

$B(\tau^- \to \mu^-\mu^+\mu^-) < 4.6 \times 10^{-8}$

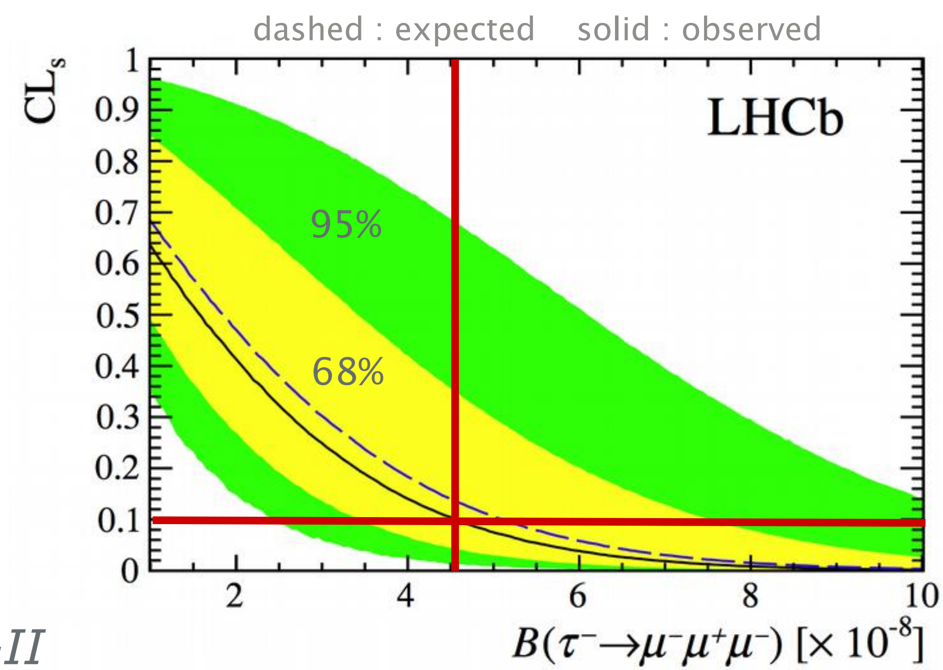
@ 90% C.L.

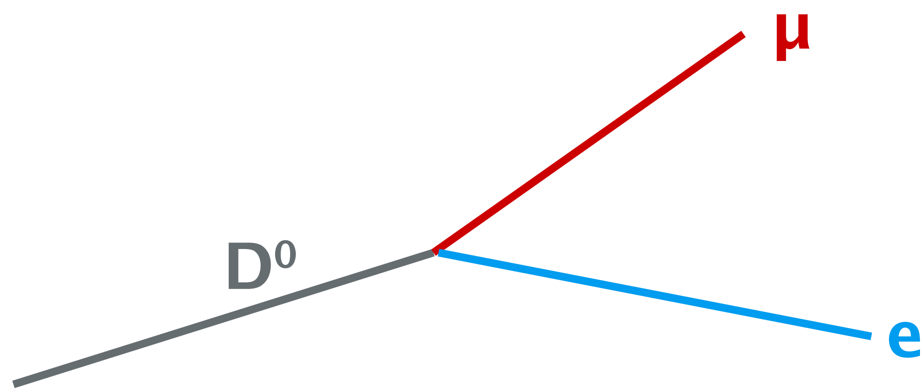
Belle 2.1×10^{-8} @ 90% C.L.

BaBar 3.3×10^{-8} @ 90% C.L.

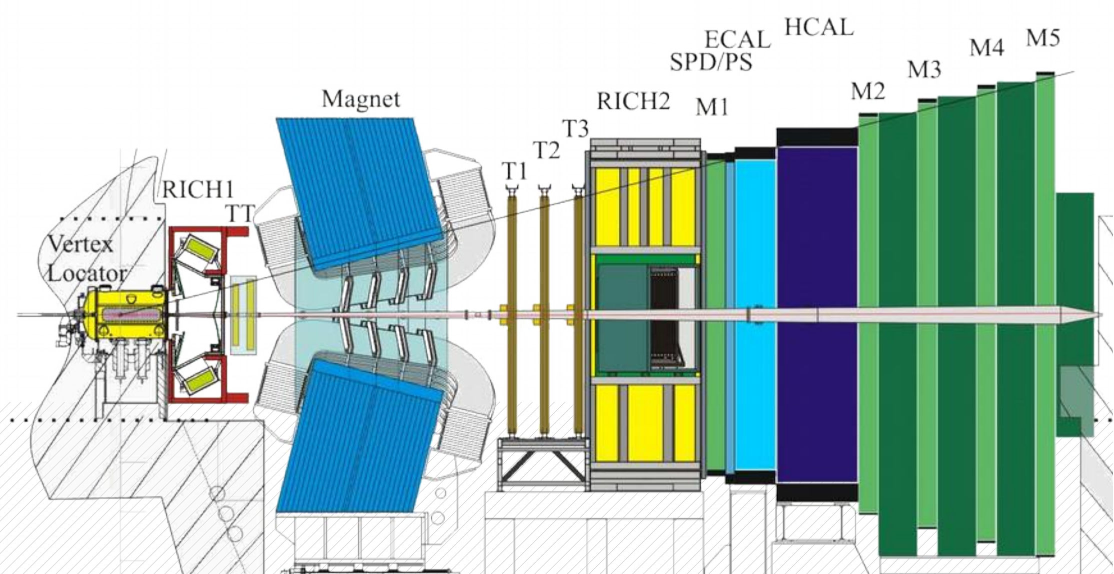
@Run2: LHCb may overtake Belle

… which will then be overtaken by Belle-II




μ
D0
e

e detection


HCAL
ECAL
SPD/PS
M5
M4
M3
M2
M1
RICH2
Magnet
T3
T2
T1
RICH1
TT
Vertex
Locator

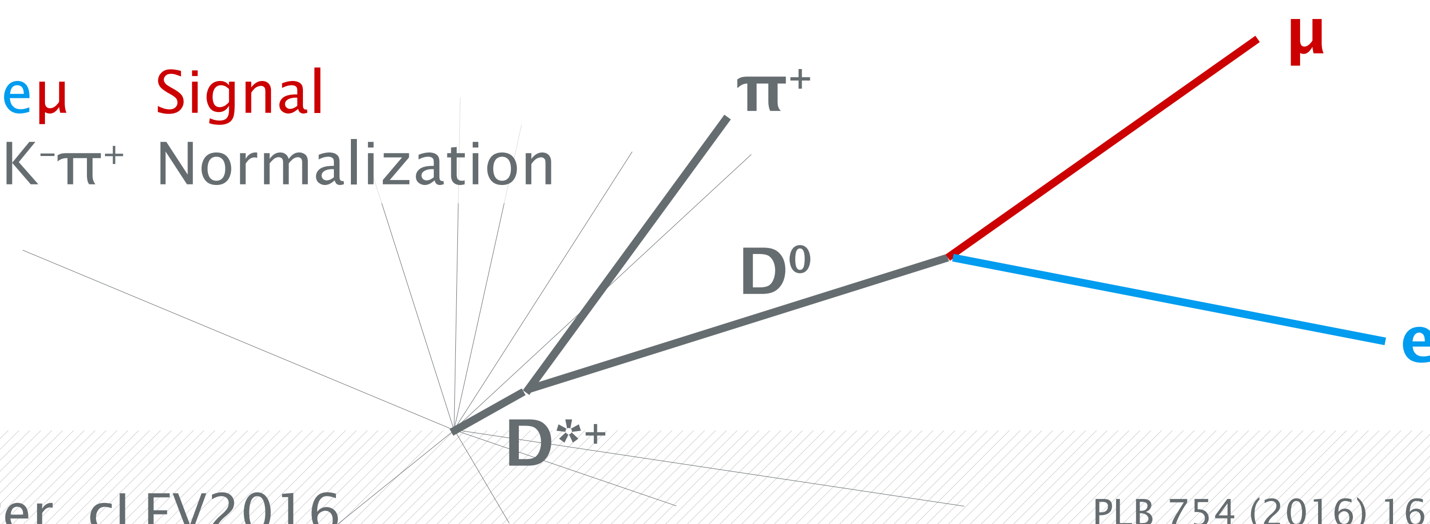
$D^0 \rightarrow e\mu$

Belle : $Br(D^0 \rightarrow e\mu) < 2.6\times10^{-7}$ (90% CL)

RPV SUSY : $\sim10^{-7}$
Leptoquarks : 4×10^{-8}

LHCb analysis based on 3 fb^{-1} collected @ $\sqrt{s}$ = 7 & 8 TeV

$D^{*+} \rightarrow D^0\pi^+$
↳ $D^0 \rightarrow e\mu$ Signal
↳ $D^0 \rightarrow K^-\pi^+$ Normalization



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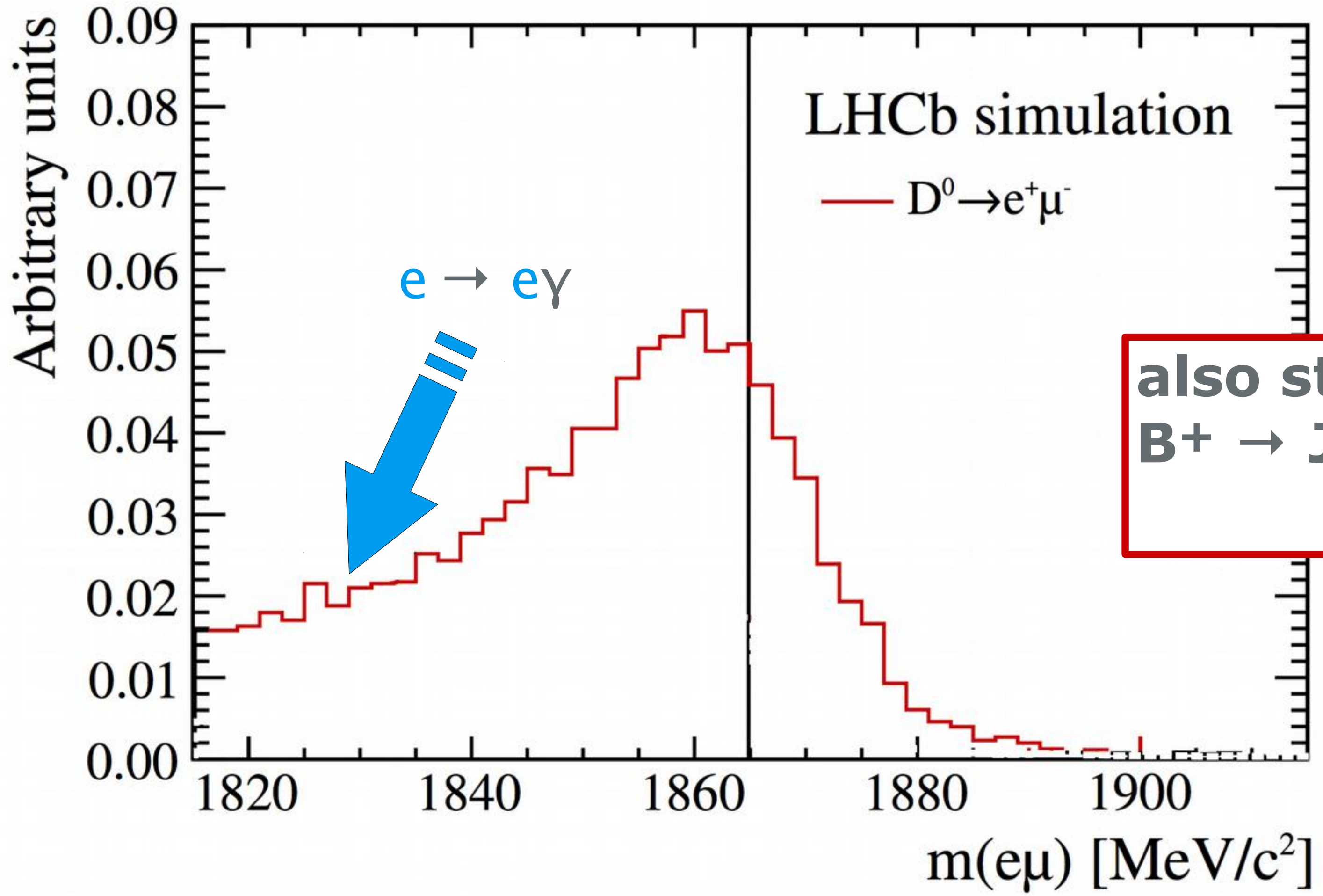
Bremsstrahlung



also study w/ $B^+ \to J/\Psi\, K^+$
↳ e^+e^-

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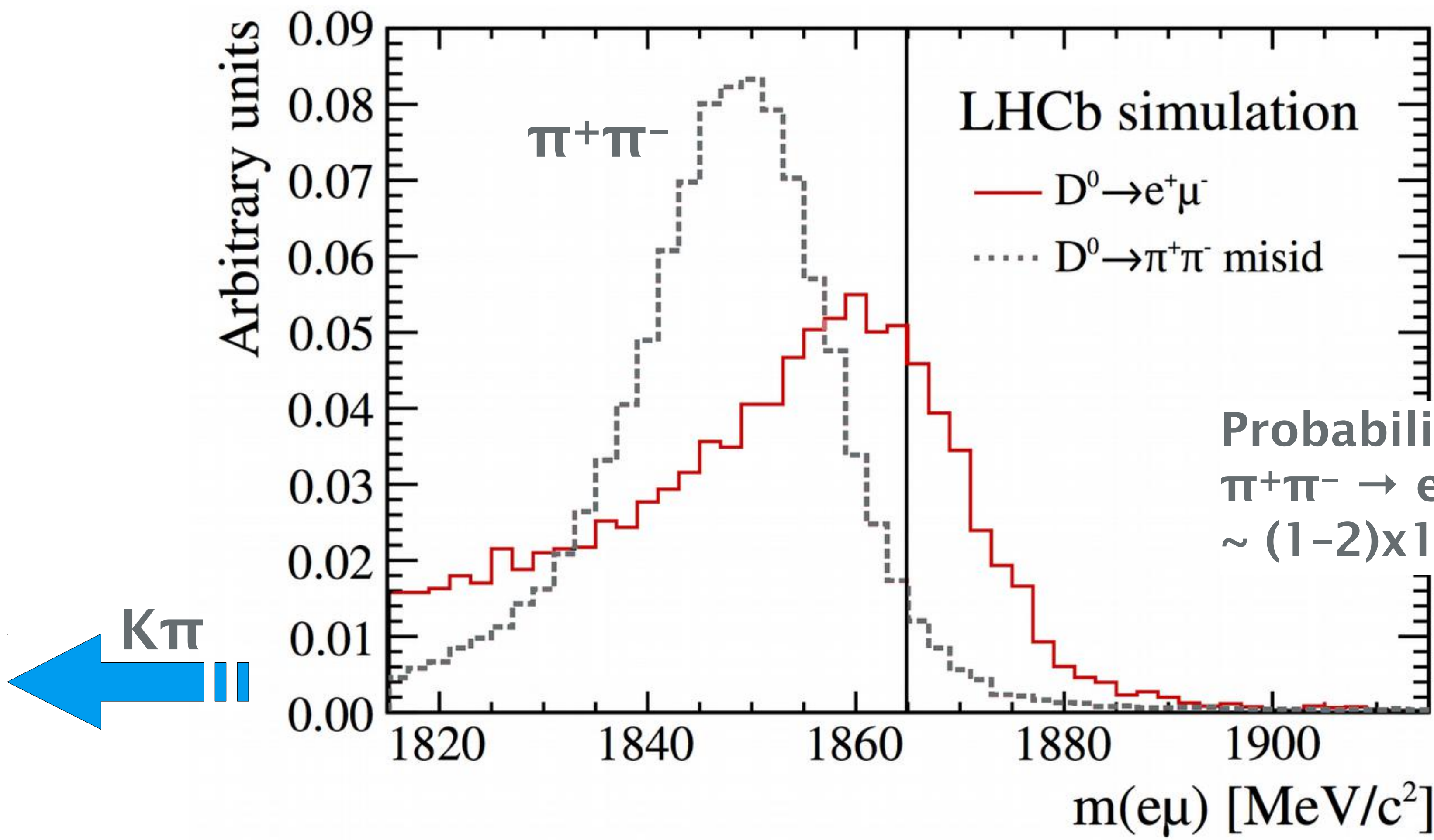
Mis-Identification



Probability for $\pi^+\pi^- \rightarrow e\mu$ mis-ID ~ (1–2)x10^{-8}

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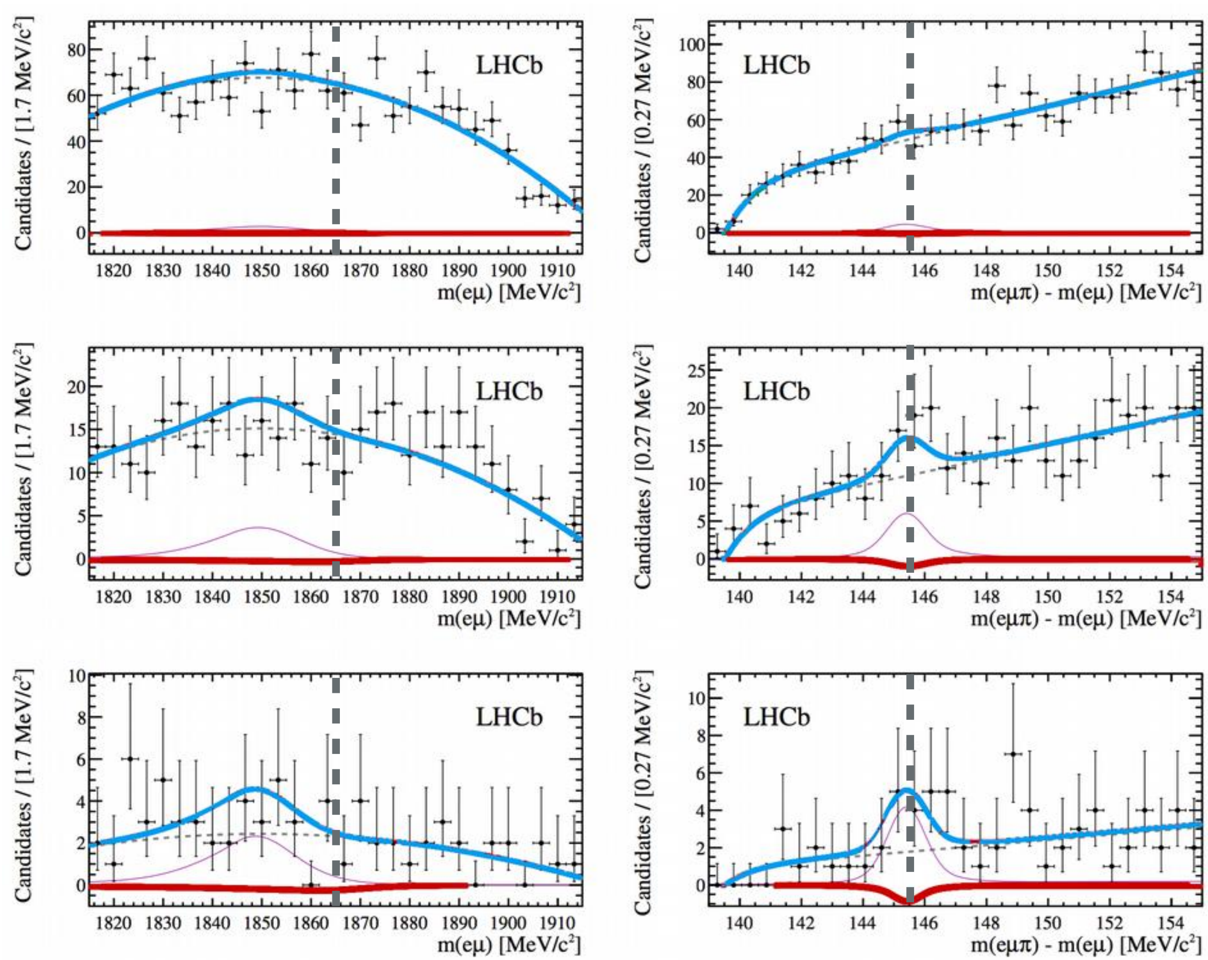
Unbinned simultaneous fits

BKGD-like

intermediate

Signal-like



Signal + bkgd

$D^0 \to e\mu$ (signal)

-7±15 events

m(eμ) → M_D **m(eμπ)-m(eμ) → M_{D*}-M_D**

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Result

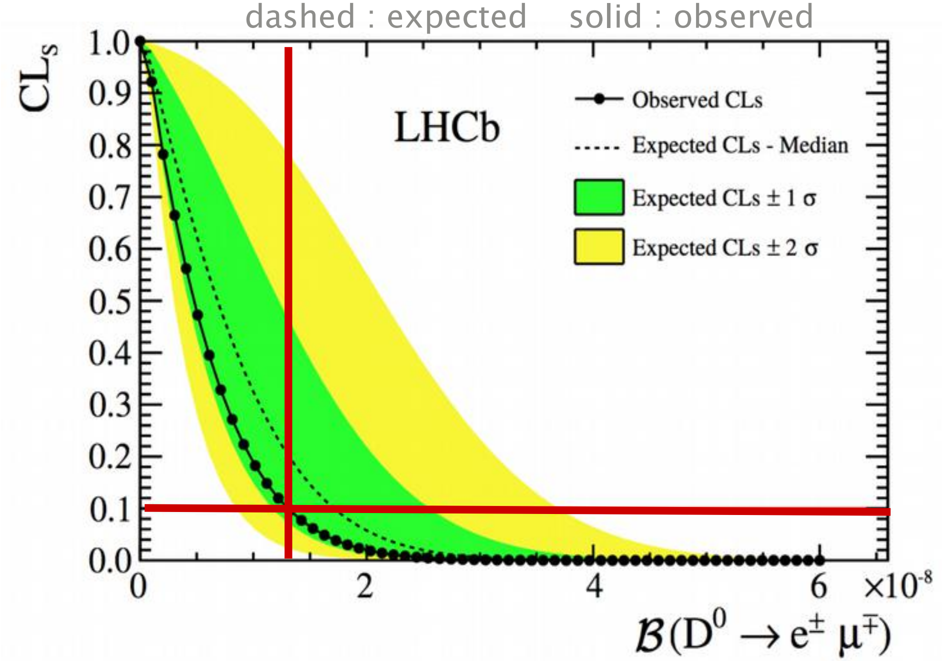
$$\frac{\mathbb{P}(\theta_{up}(X) < \theta|\theta)}{\mathbb{P}(\theta_{up}(X) < \theta|0)} \leq \alpha' \text{ for all } \theta.$$

- Robust analysis method
- Statistics limited
- No significant evidence for excess of events

$B(D^0 \to e\mu) < 1.3 \times 10^{-8}$

@ 90% C.L.

dashed : expected solid : observed



20x improvement over previous result
Effectively deal with backgrounds
Bremsstrahlung complicates analysis
Difficult to do at e^+e^- colliders

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Other channels under investigation

$B_{(s)} \rightarrow e\mu$

$B^0 \rightarrow K^{*0} e\mu$

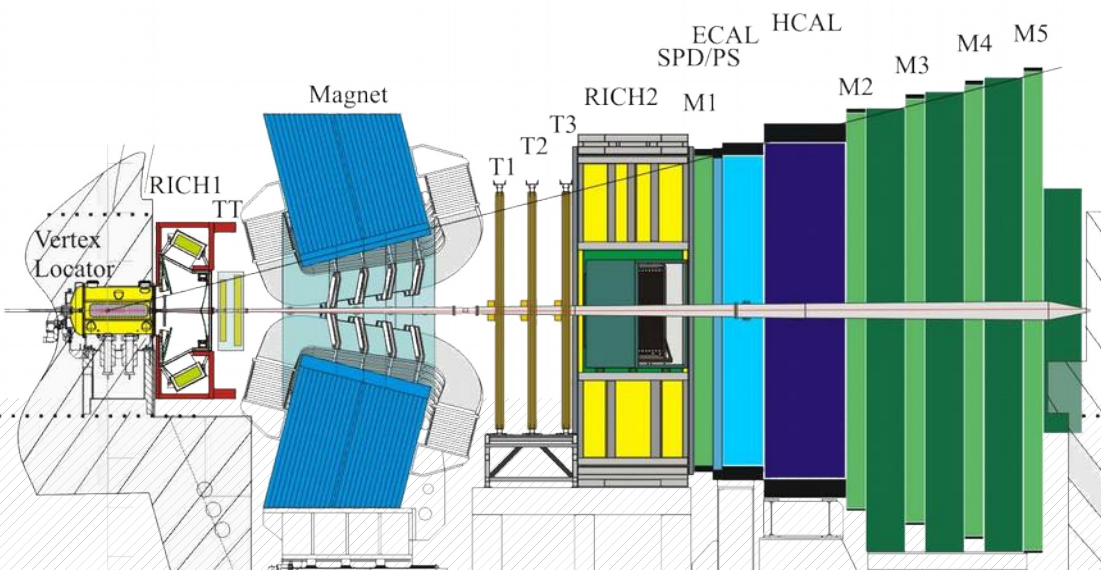
$B_s \rightarrow \Phi e\mu$

$B_{(s)} \rightarrow J/\Psi(\rightarrow e\mu)\ X$

$B^+ \rightarrow K^+ e\mu$

Expect to improve existing limits

Opportunities for τ detection



Some existing limits

$J/\Psi(1S)$	$\rightarrow \mu\tau$	$< 2\times10^{-6}$
$\Upsilon(1S)$	$\rightarrow \mu\tau$	$< 6\times10^{-6}$
$\Upsilon(2S)$	$\rightarrow \mu\tau$	$< 3\times10^{-6}$
$\Upsilon(3S)$	$\rightarrow \mu\tau$	$< 3\times10^{-6}$
Z^0	$\rightarrow \mu\tau$	$< 1\times10^{-5}$
h^0	$\rightarrow \mu\tau$	$< 1.5\%$
$J/\Psi(1S)$	$\rightarrow e\tau$	$< 9\times10^{-6}$
Z^0	$\rightarrow e\tau$	$< 1\times10^{-6}$

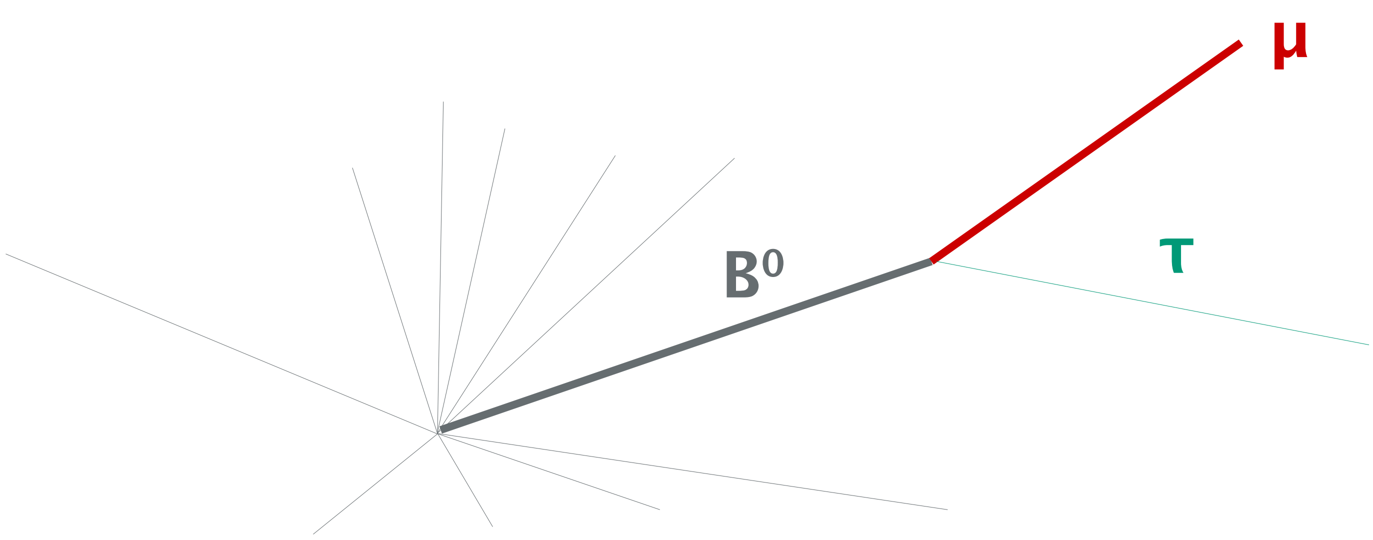
$O(\text{few} \times 10^{-6})$

@ 90-95% CL

Particle Data Group

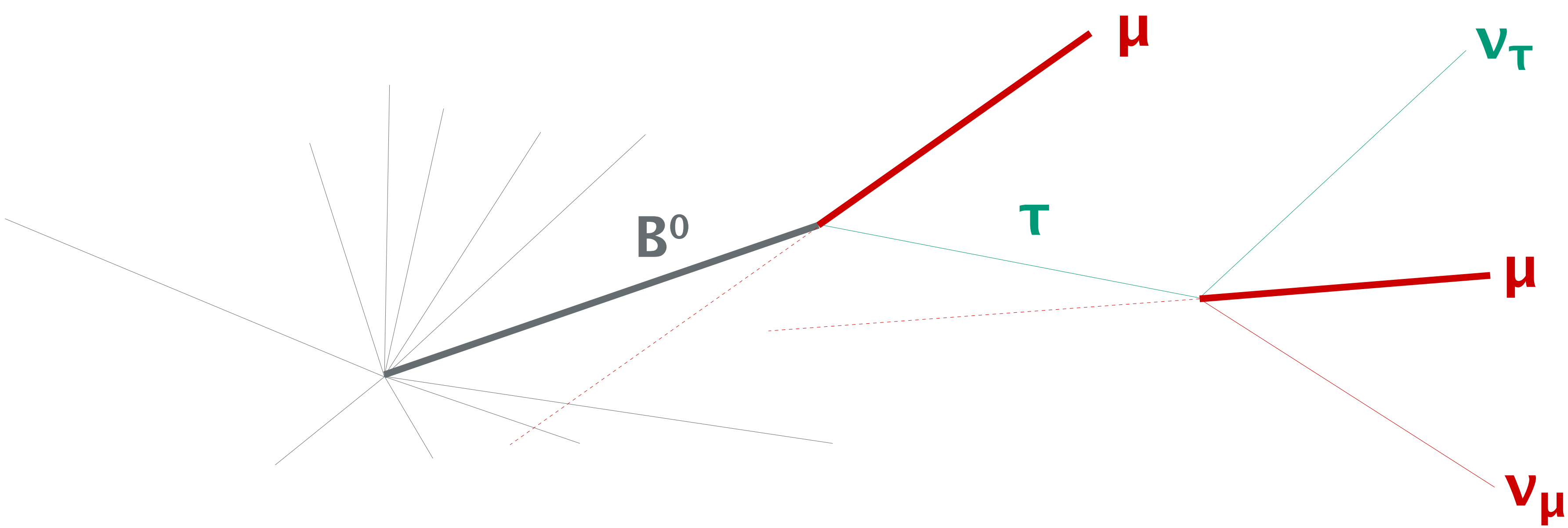
Reconstruction – I

Interesting possibility
Short lifetime prohibits direct detection



Reconstruction – II

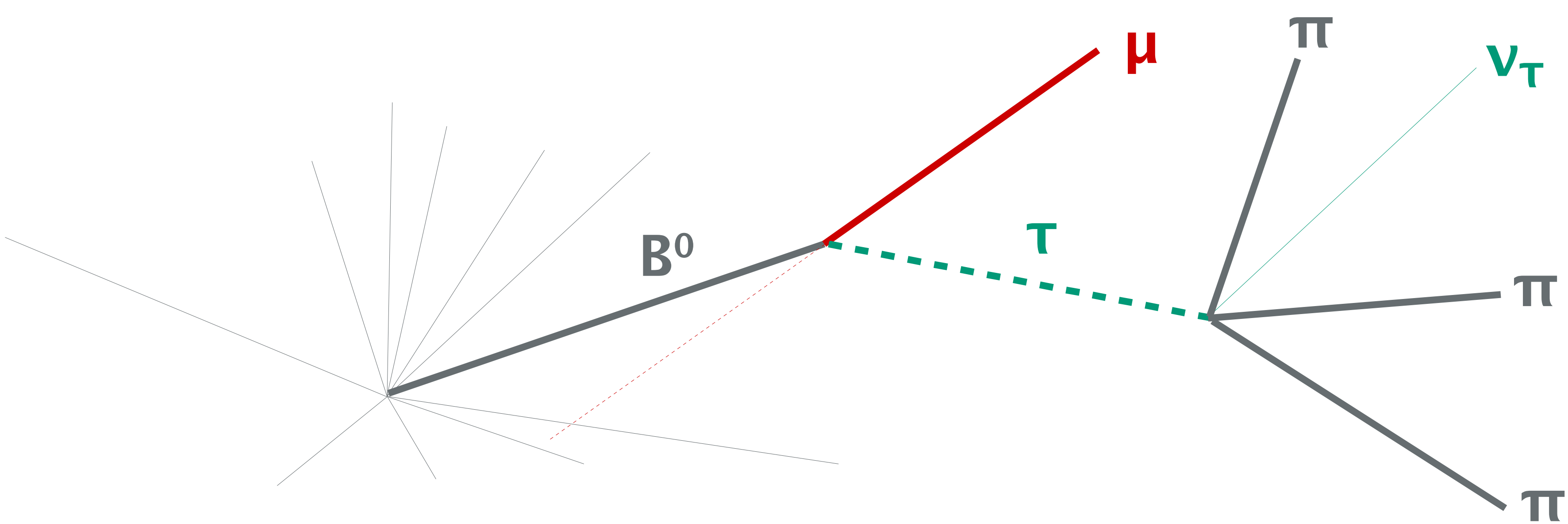
Interesting possibility
Short lifetime prohibits direct detection
Neutrinos remain undetected



Reconstruction – III

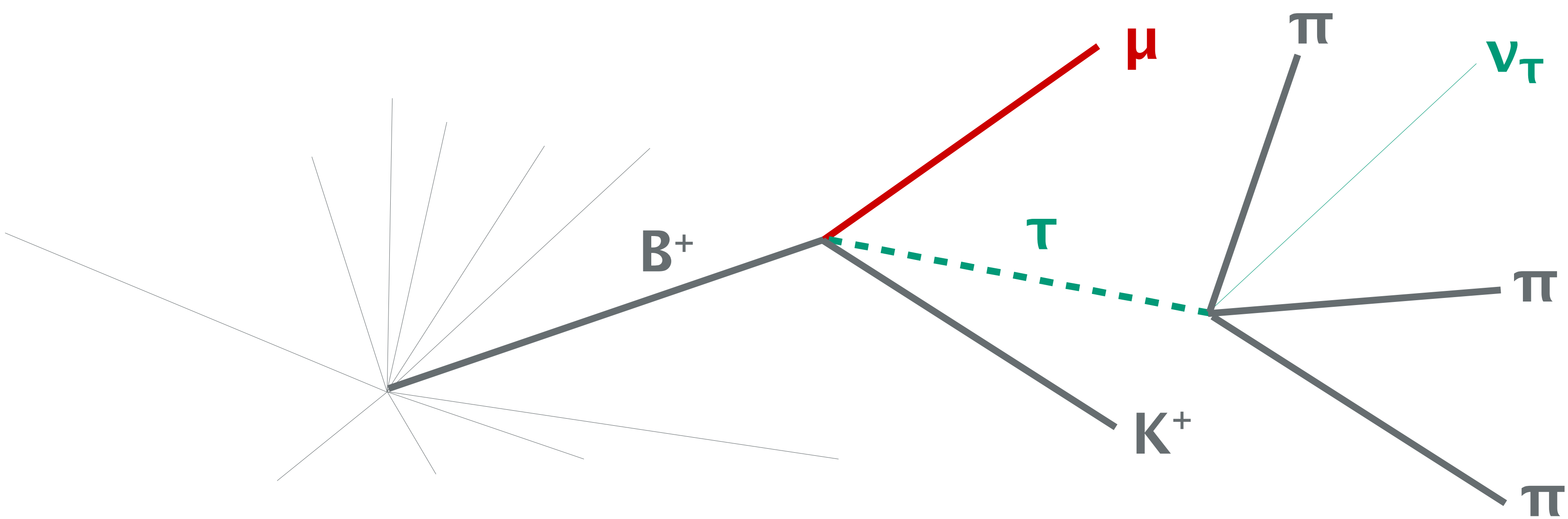
Interesting possibility
Short lifetime prohibits direct detection
Neutrino remains undetected

Br ~ 9%



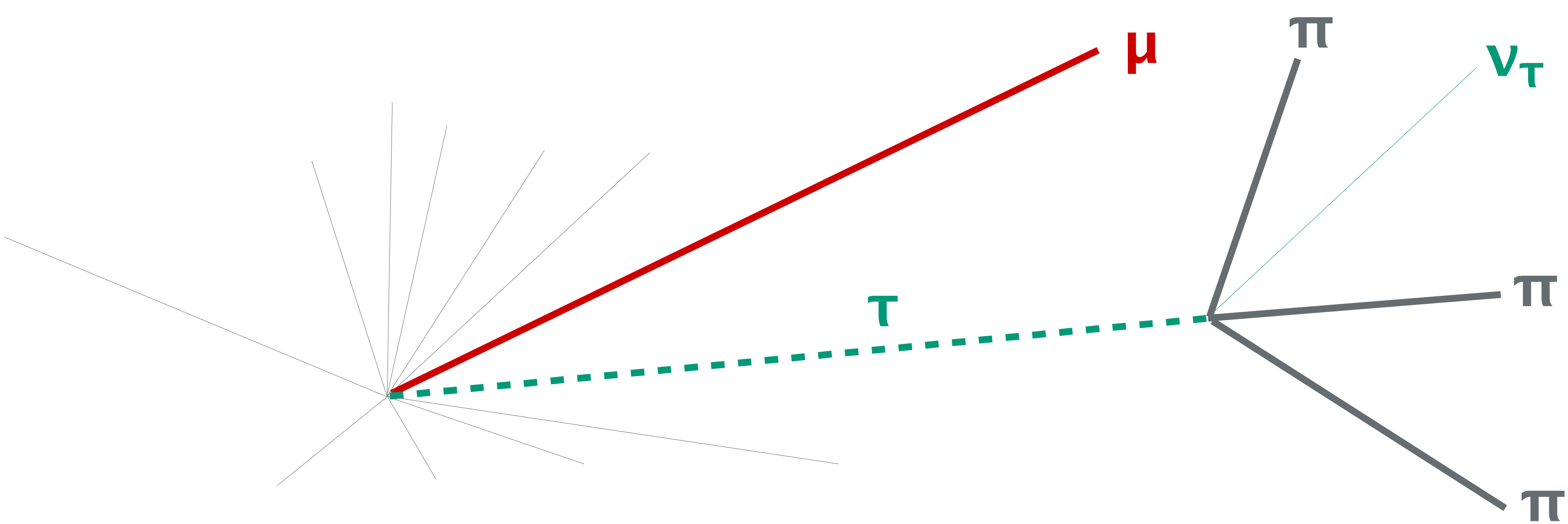
Reconstruction – IV

Interesting possibility
Short lifetime prohibits direct detection
Neutrino remains undetected

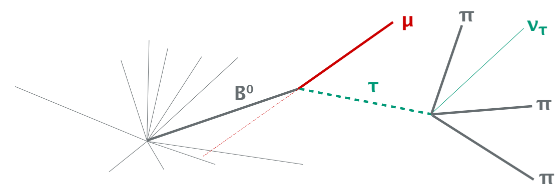


Reconstruction – V

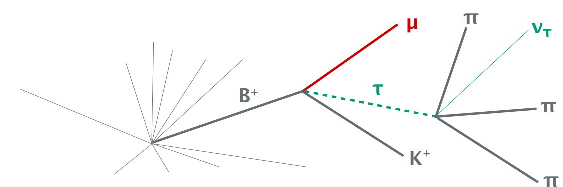
Interesting possibility
Short lifetime prohibits direct detection
Neutrino remains undetected



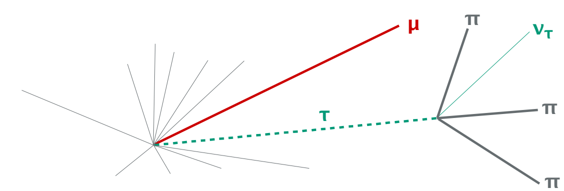
Possibly interesting channels



$B_{(s)} \rightarrow e/\mu\tau$



$B^+ \rightarrow K^+ e/\mu\tau$



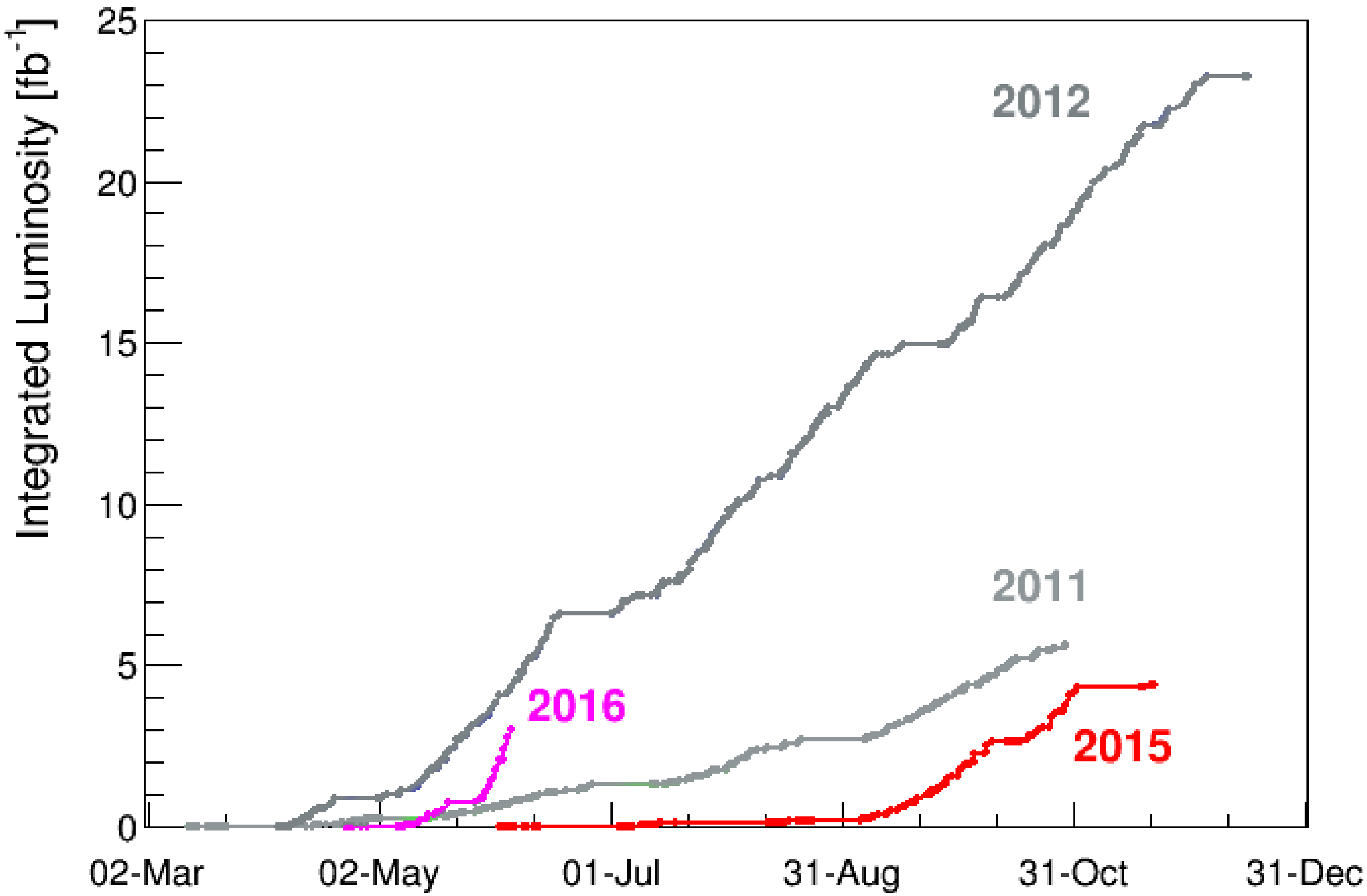
$\Upsilon(nS) \rightarrow e/\mu\tau$

Benefit from $\overline{B}^0 \rightarrow D^{*+}\tau\overline{\nu}_\tau$

Phys. Rev. Lett. 115, 111803 (2015)

Conclusion

LHC run II has started



Take away message

LHCb : diverse program studying flavor physics with all three quark & lepton generations

With LHC **Run-I** data **LHCb** sharpened limits for many LFV, LNV, and BNV channels

No significant deviations from **SM** seen

Demonstrated sensitive **BSM** searches @ hadron collider

Many more options around, lots of additional data expected in **Run-II** (just restarted) & **Run-III**

Thank you for your attention!